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THE IDENTIFICATION OF ROCK TYPES IN AN ARID REGION BY AIR PHOTO--ETC(U)

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Judy Ehlen

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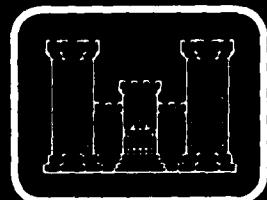
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Air photo pattern criteria to identify rock types in an arid environment were evaluated for their usefulness and accuracy by stereo air photo analysis and field verification. The criteria came from published literature and from unpublished in-house research. In general, the unpublished criteria proved the most useful. New criteria to identify granitic rocks were successfully tested, and criteria for quartzite and andesitic rocks were identified. In addition, a basis was laid to develop criteria to identify metamorphic rocks by composition on aerial photography. →		

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Sixteen lithologic units were identified and mapped on 1:100,000 scale stereoscopic panchromatic aerial photography. Lithologic predictions were based on detailed analyses of the photo pattern elements of landform, drainage, photo tone, and photo texture. Limited field checking showed that the lithologic predictions were generally correct. In addition, the boundaries of the lithologic units, not verified in the field, but determined from detailed photo analysis, compared favorably with boundaries shown on published geologic maps.

PREFACE

This study was conducted under DA Project 4A161102B52C, Task C, Work Unit 0010, "Indicators of Terrain Conditions." The study was done under the supervision of Dr. Jack N. Rinker, Team Leader, Center for Remote Sensing; and Mr. M. Crowell, Jr., Director, Research Institute.

COL Daniel L. Lycan, CE was Commander and Director and Mr. Robert P. Macchia was Technical Director of the Engineer Topographic Laboratories during the study period.

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TABLES OF CONTENTS

	PAGE
PREFACE	1
ILLUSTRATIONS	3
TABLES	4
INTRODUCTION	5
PROCEDURES	8
RESULTS	10
DISCUSSION	25
Sedimentary Rocks	25
Igneous Rocks	28
Metamorphic Rocks	30
CONCLUSIONS	33
REFERENCES I	
The Fort Bliss Area	34
REFERENCES II	
The Interpretation of Geology on Aerial Photography	36
APPENDIX	
Predictions of Lithologic Types	39

ILLUSTRATIONS

NUMBERS	TITLE	PAGE
1	Location of the Fort Bliss, Texas/New Mexico Research Area, Which Encompasses Approximately 650,000 Hectares	6
2	The Locations of Places in The Fort Bliss Area Discussed in the Text	7
3	Lithologic Units in the Study Area	24
4	The Central Part of the Franklin Mountains Showing the Layered Units L1, L2, L3, L4 and L5 and the Non-Layered Units N1 and N2	38
5	Close-up of the Marble Forming Unit L1.	39
6	Quartzites of Unit L2, Just North of the Transmountain Highway	40
7	Unit L4 at the Southern End of the Franklin Mountains	42
8	Stair-Step Topography in Unit L5 Near Charley Tank in the Hueco Mountains	43
9	Units L5 and L8 Near Campbell Tank	44
10	The Southern Hueco Mountains, Showing Layered Units L6, L7, and L8, and Non-Layered Units N3 and N4	46
11	Units L5, L8, and L10 along the Northern Otero Mesa Escarpment	47
12	Unit L9 in the Sacramento Mountains	48
13	Knob of Unit N1 along the Transmountain Highway in the Franklin Mountains	50
14	Aerial Oblique View of Unit N1 in the Jarilla Mountains	51

ILLUSTRATIONS (Continued)

NUMBERS	TITLE	PAGE
15	Stereo Pair of Unit N2 North of the Transmountain Highway	51
16	Units N3, N4, N5, and N6 in the Organ Mountains	52
17	Unit N3 at Hueco Tanks	53
18	Unit N4 in the Jarilla Mountains	54

TABLES

NUMBER	TITLE	PAGE
1	Rock Type Identification Criteria on Aerial Photography for Arid Regions	11
2	Photo Patterns of the Lithologic Units in the Study Area	18
3	Origins and Compositions of the Lithologic Units in the Study Area as Determined from Photo Analysis, with Field Names	23
4	Correlations Between Sedimentary Photo Mapping Units and Published Geological Data	26
5	Correlations Between Metamorphic Photo Mapping Units and Published Geological Data	32

THE IDENTIFICATION OF ROCK TYPES IN AN ARID REGION BY AIR PHOTO PATTERNS

INTRODUCTION

Photo patterns useful for separating rock types by origin, i.e. igneous, sedimentary, or metamorphic, have been identified in previous work in air photo analysis.* In published works, photo patterns are presented in two ways:

- (1) as partial lists of characteristics defining a particular rock type, or
- (2) as applications of photo analysis methods, usually in narrative form, to the rocks in a specified area.

Most of these sources discuss photo patterns and rock type identification criteria in the second manner. Although published rock type identification criteria may be valid for a particular site, their applicability to other geographic and/or climatic regions has not been determined.

In general, sedimentary rocks are the easiest to identify on aerial photography because stratification (layering) frequently shows as continuous banding patterns. Separation of sedimentary rocks by type is also relatively easy, in part because much work has been done and identification criteria are numerous. Igneous rocks can also be identified relatively easily because they are highly variable in photo pattern. This is to be expected, because they are highly variable in composition and form. However, it is more difficult to identify specific igneous rock types than specific sedimentary rock types on stereo aerial photography because only the more obvious identification criteria have been used as indicators. Igneous rocks can be identified by type because of the strong relationship between photo tones and rock color and composition. In the published literature, typical air photo patterns are presented for some igneous and sedimentary rocks, including basalt, granite, shale, sandstone, and limestone.

Metamorphic rocks are the most difficult to identify and separate, and as yet no photo patterns have been recognized that enable geologists to deduce the composition of metamorphic rocks on aerial photography. Metamorphic rocks tend to retain characteristics of the parent rock, such as layering if they were sedimentary, and this can lead to confusion in aerial photographic interpretation. In addition, sharp boundaries between metamorphic rock types are usually absent. Some metamorphic rock photo patterns have been presented in the literature by Belcher, et al. and von Bandat and in *Military Geology* on the basis of structure/ texture, i.e. gneiss, schist, or

* See references for a listing of published work concerning air photo analysis of rock types.

slate.¹ Identification criteria have also been suggested by von Bandat for such rocks as serpentine and marble.²

The prior incomplete treatment of rock type identification criteria, together with questions as to their accuracy and universality, provided the basis for this study. Many of these rock type identification criteria, although characteristic of the rock as studied in the field or in a hand specimen, cannot be seen on vertical aerial photography, whereas other patterns or criteria as described in the literature are found to be severely restricted when carefully analyzed. For instance, many photo patterns are restricted by climate, and this fact has been inadequately considered in the published literature. In addition, ETL research over the years casts doubts, or at least places restrictions, on some well-publicized criteria. Thus, the objectives of this study were to test and evaluate existing criteria to identify rock types on aerial photography in an arid environment and to develop new criteria. The usefulness and accuracy of recognized criteria were evaluated by using them to identify rock types on aerial Fort Bliss area contains all three kinds of rocks, it was selected as a research area where rock type identification criteria can be developed, tested, and evaluated (figures 1 and 2).*



FIGURE 1. Location of the Fort Bliss, Texas/New Mexico Research Area, Which Encompasses Approximately 650,000 Hectares.

¹D. L. Belcher, et al., Igneous and Metamorphic Rocks: *Military Geology*, and Horst E. von Bandat, *Tectonogeology*.

²Horst E. von Bandat, *Aerogeology*.

* See references for a listing of material on the geology of this area.



Scale: Reduced from 1:100,000 to 1:620,000

FIGURE 2. The Locations of Places in the Fort Bliss Area Discussed in the Text.

PROCEDURES

The photo analysis was done on Defense Mapping Agency 1:100,000 scale, 9- by 9-inch stereoscopic panchromatic aerial photography, flown by Mark Hurd in 1973, assembled as an uncontrolled photomosaic. The study area was laid as one photo mosaic, facilitating correlations between widely separated areas. The photo analysis was done exclusively by detailed stereo study. Supplementary U.S. Air Force 9- by 9-inch panchromatic stereoscopic aerial photography, at a scale of 1:50,000 (AF 69 - 35, 1969; and AF 71 - 10, 1971), was occasionally used to resolve problems related to scale.

The photo analysis procedures used in this study were developed by Robert E. Frost.³ The procedures involve detailed stereoscopic analysis of photo patterns so that the various components or pattern elements of the landscape - landform, drainage, erosion, deposition, vegetation, photo tones, photo textures, culture, and special features - can be defined. This method of analysis has been applied previously on regional and local scales to identify rock types in an arid environment.⁴ In this present study, only landform, drainage (plan, and gradient and cross section), photo tones, and photo textures were considered. Special features such as jointing and dip and strike relationships were included under landform.

Because rock type cannot be observed directly on aerial photography, it must be derived inferentially from analyses of the above pattern elements. Drainage and landform are the most important because certain rocks or combinations of rocks produce characteristic landform and drainage patterns. For example, interbedded sedimentary rocks often produce stair-step topography, and discontinuous drainage is associated with limestone. In addition, photo tones are related to rock color and composition; for example, basalt, a dark gray to black rock, is formed of dark-colored minerals, and its photo tone ranges from dark gray to black. The term photo texture refers to the surface of the rock as it appears on the stereoscopic aerial photography. Photo textures are related to erodability, which is in part a function of grain size and hardness. A fine-grained rock, for example, will have a smooth, velvety, soft photo texture.

³Robert E. Frost, et al., *Photo Interpretation of Soils and Rocks*, 1953.

⁴Judy E. Hulen, *Photo Analysis of a Desert Area*, 1976.

Analysis of these pattern elements provides clues to rock type, and when combined and compared to rock type identification criteria, the clues become the basis for predicting rock types. Table 1 shows rock type identification criteria by the pattern elements of landform, drainage, photo tone, and photo texture. Published criteria are shown in this type and newly-developed criteria, in italics.

Geologic structure, such as joints, faults, and dips and strikes, also play a role in rock type analysis, because changes in structure can change landform and drainage patterns. For instance, in an arid environment, steeply-dipping limestones are much more angular and rugged in appearance than gently-dipping limestones. Consequently, understanding structural changes is necessary to identify and correlate the various lithologies in an area.

In this study, each lithologic unit identified on the photography was analyzed to determine its origin, i.e. igneous, sedimentary, or metamorphic. Bedrock was separated into two groups - layered and non-layered. Layering is most typical of sedimentary rocks. The layers or beds, normally continuous horizontally, result from sequential deposition of materials of different compositions. Although sequential lava flows (igneous rocks) do form layers, this layering can be differentiated from sedimentary bedding on aerial photography by the darker tone of the lava, by the rougher photo texture of the lava, and by the different drainage and erosional characteristics of the materials. Layering in metamorphic rocks, seen on aerial photography, is usually "remnant," i.e. a mildly metamorphosed sedimentary rock retains its layered/bedded structure. Differentiation between "remnant" layering and sedimentary bedding is difficult, and additional photo characteristics of either sedimentary or metamorphic origin must be identified to differentiate between them. For instance, landforms in sedimentary rocks are controlled by the bedding, whereas "remnant" layering in metamorphic rocks exerts no control on landform. In general, however, rock units that exhibit layering on aerial photography are most likely sedimentary rocks.

The layered rocks were separated into lithologic units based on layering patterns, differences in overall photo tone, slope, resistance to erosion, and ridge crest characteristics. The vertical relationship or stratigraphic position of sedimentary rocks generally represents the sequence in which they were deposited, thus the lowest unit is usually the oldest and the highest unit is the youngest. The convention of describing sedimentary units beginning with the oldest (lowest) is followed here.

The non-layered rocks, either igneous or metamorphic in origin, are irregular in outline and usually exhibit a rougher photo texture than layered rocks. In the Fort Bliss area, the non-layered rocks consistently interrupt the continuity of sedimentary bedding, which suggests they are igneous in origin. Subdivision of the non-layered rocks was difficult because of their variation and the limited areal extent of most of the units. They are separated into individual units on the basis of photo tone; photo texture; ridge crest characteristics; and the prevalence, degree, and type of jointing.

Most of the lithologic units identified on the photography were visited in the field in at least one location. However, in the Organ Mountains, field checking was not possible because of military restrictions. Also, some units in the Hueco, Sacramento, and Jarilla Mountains were not visited because of difficult access.

After the photo analysis and field work were completed, the lithologic units identified on the aerial photography were compared to published geological data. This confirmed the locations of contacts and, in addition, provided information on the composition of rock units not visited in the field. The criteria used to identify the various lithologies in the study area were evaluated as to their usefulness and accuracy, and new criteria were then defined.

RESULTS

Sixteen lithologic units were identified on the aerial photography. Ten of these units are layered (units L1 through L10), and six are non-layered (units N1 through N6). The lithologic units are shown in figure 3. Each of the lithologic units was evaluated in terms of its characteristic landform and drainage patterns (plan, and gradient and cross section), and its photo tone and photo texture. A summary of the characteristics for each lithologic unit is presented in table 2, and descriptions and illustrations of the units are in the appendix. Analysis of photo pattern elements provided the basis for rock type predictions. Twelve of the 16 units were visited in the field in at least one location. The field data are presented, along with the data derived from photo analysis, in the appendix. A summary of the rock type identifications from photo analysis and field evaluations is shown in table 3.

TABLE I. Rock Type Identification Criteria on Aerial Photography for Arid Regions.*

Rock Type	Landform	Drainage		Photo Tone (Pan)	Texture
		Plan	Gradient and Cross Section		
Gneiss	Irregular boundaries (x)	Angular dendritic	[U-shaped cross section]	Light (?)	Rough
	Steep-sided, sharp-crested ridges, often parallel	Fine-to-medium texture	Narrow, V-shaped cross section	Banding not apparent	Uneven
	Steep-sided, sharp-crested hills	Abrupt angular bends	Slope gradients	Can be dark owing to desert varnish	Knobby
	<i>Long slopes</i>	90° intersections (?)			
	<i>No talus</i>				
	<i>High relief, rugged</i>				
	Parallel laminations (?)	Angular dendritic, rectangular, or trellis	Narrow, deep gullies with few branches	Light (?)	
	Moderate relief	Fine texture	Steep-sided	[Often faintly banded]	
	Fairly rugged topography	Gullies parallel	[U-shaped cross section]	Uniform	
	Usually steep attitude				
Schist	Low ridges, shallow depressions	Low ridges, shallow depressions	Open, V-shaped cross section		
	<i>Slightly rounded ridge crests</i>				
	Boundaries irregular and transitional (?)	Rectangular to rectangular dendritic or trellis	Deeply incised	Light (?)	
	Rounded, steep-sided hills, usually small (x)	Very fine texture	Steep-walled	Hilltops darker.	
	Sharp-crested, steep-sided ridges, usually aligned		[U-shaped cross section]	valleys lighter (?)	
	Elevations repeat (x)			<i>Light to dark gray as a function of origin</i>	
	Highly eroded				
Slate					

*Identification criteria, derived from the published literature (excluding those by R. E. Frost) are shown in this type. Criteria that have been developed by R. E. Frost and those working with him over the years at Purdue University (1942-56), U.S. Army Snow, Ice, and Permafrost Research Establishment (1956-60), U.S. Army Cold Regions Research and Engineering Laboratory (1960-76), and U.S. Army Engineer Topographic Laboratories (1970-present), are shown in this type. (?) indicates an item is incorrect, (?) indicates an item is unknown, (x) is being questioned, and () that it is unknown.

TABLE 1. Rock Type Identification Criteria on Aerial Photography for Arid Regions. (Continued)

Rock Type	Landform	Drainage			Texture
		Plan	Gradient and Cross Section	Photo Tone (Pan)	
Marble	Massive, rounded <i>Smooth ridge crests</i>			Light (?) Light to dark gray	Fine, smooth
Serpentine	Smoothly curving boundaries Winding ridges between elongate, cone-shaped hills (x)	Dendritic or radial Coarse texture	Steep gradient (x)	Dull, even gray	
Quartzite	Hills quite rounded Easily eroded	Angular	Steep-sided gull leys	Light to dark gray as a func- tion of origin Can be banded	Medium to coarse Uneven to rough
12	<i>Highly resistant to erosion</i> <i>High relief</i> <i>Moderately jointed</i> <i>Narrow, but slightly rounded</i> <i>ridge crests</i>				
Granite	Tors and boulder piles Boundaries smoothly curving Highly resistant to erosion Rounded, convex surfaces - whalebacks and woolacks Bold, massive dome-like hills Steep slopes A-shaped hills (?) Summit elevations not repeated Random arrangement; lack of linearity	Well-integrated den- dritic, rectangular locally (?), radial regionally; angular Sickle- or hook-shaped (pincer-shaped) in headwater areas Stream intersections near 90° or slightly acute upstream (?)	Few gullies Steep, uneven gradients Steep-sided, un- even V-shaped cross section Straight-sided on major portions of side-slopes (?)	Light [Banded] Uniform	Choppy surface Rounded and lumpy Coarse

TABLE 1. Rock Type Identification Criteria on Aerial Photography for Arid Regions. (Continued)

Rock Type	Landform	Drainage		Photo Tone (Pan)	Texture
		Plan	Gradient and Cross Section		
	Heavily jointed -- vertical and curvilinear shearing joints Pinnacles, needles and spires in highly vertically jointed rock				Ropey; blocky and angular; rough and jagged
Basalt	Jagged, well-defined boundaries Level or gently sloping plains, mesas, and plateaus; forms capping Shield-shaped hills Ridges with pear-shaped appendages and narrow connections (x) Talus at base of slopes Vertical escarpments Stepped (terraced) canyon walls As ejecta, cone-shaped hills <i>Flowmarks</i> <i>Flows can be lobate in shape</i>	Parallel regionally on flows Poorly developed, mainly (?) internal on flows Coarse texture on flows Radial on volcanos Fine texture on volcanos	Few to no gullies Cross section varies Box-shaped cross section Banded where flows interlay- ered (?)	Very dark gray to black, fre- quently with light spots Banded where flows interlay- ered (?)	
	Columnar joints Highly vertically jointed				

TABLE 1. Rock Type Identification Criteria on Aerial Photography for Arid Regions. (Continued)

Rock Type	Landform	Drainage		Photo Tone (Pan)	Texture
		Plan	Gradient and Cross Section		
Andesite	<i>Stepped canyon walls</i> <i>Talus</i>	<i>Dendritic</i>	<i>V-shaped cross section</i>	<i>Medium to dark gray</i>	<i>Rough to blocky</i>
	<i>Sleep slopes</i>				
	<i>Conical hills, plateaus</i>				
Limestone	Transitional boundaries (x) Moderate to steep slopes Layered Forms caprock Sinkholes -- solution features can be found, but are not characteristic of limestone development in an arid en- vironment	Well-developed angular dendritic, discontinu- ous, and <i>rectangular</i> Fine-to-medium texture	Flat-bottomed gullies <i>Steep sides on</i> gullies <i>Box-shaped cross</i> section	Uniform, light gray Can be white Banded	<i>Angular to</i> blocky
	<i>High relief</i>				
	<i>Angular, sharp, narrow ridge</i> <i>crests in tilted rock</i>				
	<i>Very resistant to erosion</i>				
	<i>Rounded, lobate, or scalloped</i> <i>hills in plan view in flat-</i> <i>lying or gently dipping rocks</i>				
	<i>Highly fractured</i>				

TABLE 1. Rock Type Identification Criteria on Aerial Photography for Arid Regions. (Continued)

Rock Type	Landform	Drainage		Photo Cross Section	Photo Tone (Pan)	Texture
		Plan	Gradient and Cross Section			
Shale	Rugged topography (badlands) Steep-sided, rounded hills Rounded ridge crests Highly dissected <i>Easily eroded</i>	Dendritic Very fine texture and high density Meandering or wiggly on valley floors Long gullies <i>Many high-order tributaries</i>	Steep-sided, sag and swale (?) Flat, open, V- shaped cross section Steep gradients (?) <i>Low gradient</i>	Uniform (?) Light (?) Dull Faintly banded <i>Light to dark gray as a function of origin</i>	Soft, smooth, velvety, and fine	
Sandstone	Distinct linear boundaries (?) Resistant to erosion Bold, massive hills Forms caprock; elevations repeat	Angular dendritic to rectangular Medium-to-coarse texture <i>Joint-controlled</i> <i>Long, straight, stream segments</i>	No gullies (?) Incised V-shaped cross section <i>Even gradient</i>	Light-to-medium- gray	Rough, uneven, and slightly knobby	
	Layered Streamlined shapes <i>Broad, gently rounded ridge crests</i>					
	Narrow, steep-sided valleys <i>often near-vertical slopes</i>					
	Jointed -- usually two sets at 90° -- <i>vertical joints</i>					
	<i>Often very heavily jointed</i>					

TABLE 1. Rock Type Identification Criteria on Aerial Photography for Arid Regions. (Continued)

Rock Type	Landform	Drainage		Gradient and Cross Section	Photo Tone (Pan)	Texture
		Plan	Photo			
Interbedded Sedimen- tary Rocks (flat- lying)	Terraced hillsides (stair- step topography: [beds must be 25 feet thick or more] - <i>beds must be more</i> <i>than 1 m thick</i>)	Dendritic, can be angu- lar or <i>rectangular</i> Fine-to-medium texture, if thin-bedded; fine texture, if thick-bedded	Few gullies (?) <i>Blocky; modified</i> <i>shaped cross</i> <i>section</i>	Banded, may be faint Gullies light where limestone present	Texture of main rock type will predominate if thin-bedded Generally <i>blocky</i>	
	Terracing follows contours Shale forms gradual slopes; limestone and sandstones, steep slopes Steep well-rounded hills where thin-bedded No solution cavities in lime- stones - <i>depends on climate</i> <i>during formation</i>			Sandstone darker than lime- stone		
	<i>Knobs</i>	<i>Blocky plateaus</i>				
		<i>Rounded, lobate, scalloped</i> <i>hills in plan view</i>				

TABLE 1. Rock Type Identification Criteria on Aerial Photography for Arid Regions. (Continued)

Rock Type	Landform	Drainage		Gradient and Cross Section	Photo Tone (Pan)	Texture
		Plan	Photo Tone (?)			
Interbedded Sedimen- tary	Sharp, saw-tooth ridge crests - V's between teeth point down dip	Trellis, can show parallelism Fine texture	Few gullies (?)	Banded Ridges usually	Banded Ridges usually	Texture of main rock type will predominate if thin-bedded
Rocks (tilted)	Shale forms low, conical hills Straight, parallel, asymmetric ridges	<i>Often meandering</i>				
		<i>Stair-step topography where gently dipping</i>				
		<i>Rugged topography</i>				
		<i>Hogbacks, cuestas</i>				
		<i>[Sandstone the ridge former,] shale the valley former, and limestone is in between] [limestone is the ridge former where present</i>				
		<i>Rounded, lobate, scalloped hills in plan view if gently dipping</i>				

TABLE 2. Photo Patterns of the Lithologic Units in the Study Area.

Unit	Landform	Drainage		Photo Tone (Pan)	Photo Texture
		Plan	Gradient and Cross Section		
L1	Curvilinear lower boundary, linear upper boundary Slightly rounded, but sharp ridge crests Long, steep slopes	Dendritic Fine-to-medium texture	V-shaped cross section Flat bottoms	Dark gray Very faint lay- ering	Smooth, even, and fine on slopes; rough on outcrop
L2	Very resistant to erosion Forms a secondary ridge that is slightly rounded Pointed peaks protrude from slopes No jointing Moderate westward dip Linear boundaries parallel to the layers in L1	[Areal extent too lim- ited to determine] [Areal extent too lim- ited to determine]		Dark and light banded	Rough and blocky
L3	Linear boundaries, parallel to layers in L2 and L4 Broadly rounded ridges and spurs Short, moderately steep, side slopes Moderately resistant to erosion Moderate-to-steep westward dip	Dendritic No high order trib- utaries	V-shaped cross section Steep gradient	Faintly alter- nating dark and light gray	Lighter-toned bands are rough; dark are smooth and fine

TABLE 2. Patterns of the Lithologic Units in the Study Area. (Continued)

Unit	Landform	Drainage		Photo Tone (Pan)	Photo Texture
		Plan	Gradient and Cross Section		
L4	High relief Linear boundaries parallel to layers in L3 Ridge former - very sharp, na- row ridge crests and spurs Moderate to steep dip westward Layers differ in hardness, some protruding down slopes Steep slopes Layered	Dendritic Fine texture Gullies long and straight	Steep-sided gull- lies V-shaped cross section	Medium to very light gray	Angular and blocky
L5	Stair-step topography Rugged, highly dissected Some slopes rilled Moderate resistance to erosion Light-toned layers protrude on slopes and form ridge crests Broad, scalloped, slightly wind- ing ridge crests	Dendritic Fine texture Many high-order trib- utaries	Flat-bottomed gullies Modified V-shaped cross section Moderate gradient	Distinctly banded Light and Dark layers	Dark layers, fine; light, angular and blocky
L6	Linear boundaries, parallel to layering in L5 Long, steep, uneven slopes Swirled pattern High relief Broad ridge crests Moderate eastward dip Moderately to highly dissected	Dendritic Medium to fine texture Some meandering Higher order tributar- ies	Open V-shaped cross section Moderate-to- steep gradients	Banded Medium to dark gray and light gray bands Overall tone medium gray	Smooth and even

TABLE 2. Photo Patterns of the Lithologic Units in the Study Area. (Continued)

Unit	Landform	Drainage		Photo	
		Plan	Gradient and Cross Section	Tone (Pan)	Texture
L ⁷	Linear boundaries parallel to layering in L6 Long, smooth, steep slopes Moderately dissected Rounded hill tops Fairly narrow, slightly scalloped ridge crests Moderate relief Limited outcrop	Dendritic Medium texture Some meandering	Open V-shaped cross section Low-to-moderate gradients	Medium to dark gray bands, somewhat faint	Smooth and fairly fine
L ⁸	Gentle slopes, steepening slightly in larger stream valleys Low eastward dip Undulating surface Moderate resistance to erosion Small depressions Layered	Mainly dendritic with radial, trellis, centripetal, barbed and discontinuous areas	Flat-bottomed gullies Open, broad U-shaped cross section Low, smooth gradients	Medium gray, somewhat mottled Some white gully fringes Gullies dark-toned	Smooth, rounded, and even
L ⁹	Broad, rounded, knobby ridge crests and spurs Elevations of hills/ridges repeat Very steep, smooth slopes Deep valleys Some scalloping along baseline contours in the north	Dendritic Coarse texture Angular	Flat-bottomed gullies Open V- to U-shaped cross section	Light gray	Rough and uneven Somewhat knobby

TABLE 2. Photo Patterns of the Lithologic Units in the Study Area. (Continued)

Unit	Landform	Drainage		Photo Tone (Pan)	Photo Texture
		Plan	Cross Section		
U10	Small, rounded, knobby hills Moderately to steeply dipping Swirled pattern of layers Moderate resistance to erosion, Flat-to-ridge form, h and straight	Dendritic Coarse texture Somewhat wiggly in Ridge sharpness, tributaries long and straight	V-shaped cross section Moderate grad- ients	Dark, muddy gray Faintly banded	Rounded, uneven Somewhat knobby
U11	Rugged topograph, Peaks common Long, steep, smooth slopes Bedrock at high elevations, limited in areal extent Talus slopes Heavily jointed -- vertical and curvilinear sheeting joints	Dendritic Angular bends Coarse texture Long, straight trib- utaries	Very steep grad- ients Open, V-shaped cross section	Very light gray on outcrop Light to medium gray on slopes	Rounded and lumpy
U12	Sharply V-ed ridges and spurs Long, smooth slopes Outcrop on middle and upper slopes with talus below Some vertical jointing	Dendritic Medium texture Higher order tributaries	Steep gradients Open, V-shaped cross section	Dark gray	Rough, blocky out- crop Side slopes smooth
U13	No talus Heavily jointed -- both verti- cal and curvilinear sheeting Joints Sharp ridges Rounded forms where less heav- ily jointed	Dendritic and radial Very straight third order tributaries -- form herringbone pat- tern	Tight to slightly open V-shaped cross section Even, steep grad- ients	Medium to light gray	Blocky to rounded and lumpy

TABLE 2. Photo Patterns of the Lithologic Units in the Study Area (Continued)

Unit	Landform	Plan	Drainage		Photo Texture
			Gradient and Cross Section	Photo Tone (Pan)	
N4	Inselbergs	Dendritic and radial Medium texture	Steep gradients V-shaped cross section	Medium gray	Blocky and rough on outcrop; fine to medium on slopes
	Pointed peaks				
	Long talus slopes				
	Moderately vertically jointed				
	V-shaped ridges				
N5	Limited areal extent				
	Pointed peaks	Dendritic Fine texture	Moderate to steep gradients V-shaped cross section	Light gray	Generally fine, but occasionally blocky and rough
	Talus slopes	Streams occasionally wiggly			
	Moderately vertically jointed				
	Long slopes				
	Ridge crests very slightly rounded				
	Limited areal extent				
	Extensive outcrop	Dendritic and parallel (on steep slopes)	V-shaped cross section, some- times more open	Very light gray to white	Rounded and lumpy
	Talus slopes rare	Very long, straight tributaries	Very steep grad- ients		
	Very steep, long slopes	Pincer-like pattern in headwater areas			
N6	High elevations				
	Very rugged topography with high relief	Medium to coarse tex- ture			
	Heavily jointed -- both vertical and curvilinear sheeting joints	Occasionally angular bends			
	Sharp ridges with spires				

TABLE 3. Origins and Compositions of the Lithologic Units in the Study Area
as Determined from Photo Analysis, with Field Names.

Rock Unit	Rock Origin	Identification Based on Photo Analysis	Identification Based on Field Work
L1	Metamorphic	Schist or slate	Marble
L2	Metamorphic	Quartzite and schist	Quartzite
L3	Metamorphic	Schist and quartz schist	Quartzite
L4	Sedimentary	Limestone	Limestone with shale partings
L5	Sedimentary	Limestone with shale	Limestone and shale with some siltstone and minor sandstone
L6	Sedimentary	Limestone	Limestone, with shale, sandstone, and conglom- erate
L7	Sedimentary	Limestone	Limestone (?)
L8	Sedimentary	Limestone	Limestone
L9	Sedimentary	Sandstone	Not visited in the field
L10	Sedimentary	Sandstone	Sandstone
N1	Igneous	Granitic*	Granite
N2	Igneous	Andesitic*	Quartz latite/rhyolite
N3	Igneous	Granitic	Quartz monzonite/ quartz latite
N4	Igneous	Andesitic or dioritic*	Quartz diorite/quartz monzonite/dacite
N5	Igneous	Rhyolite or diorite	Not visited in the field
N6	Igneous	Granitic	Not visited in the field

*Because the names of igneous rocks, such as granite and andesite, connote specific mineral assemblages and percentage ranges of mineral components, only general terms can be used to identify igneous rocks on aerial photography. The term "granitic" will be used in the sense of a light-colored, coarse-grained, silicic igneous rock, and includes granite, granodiorite, quartz diorite, and monzonite. "Andesitic" refers to a medium composition, i.e. between silicic and mafic, fine- to medium-grained igneous rock. The medium or intermediate range, therefore, includes latites, andesites, and dacites, but not rhyolites or basalts.



Scale: Reduced from 1:100,000 to 1:620,000

FIGURE 3. Lithologic Units in the Study Area.

DISCUSSION

The origin of each lithologic unit, i.e. igneous, metamorphic, or sedimentary, was correctly predicted in photo analysis. The rock units were easily separated into layered and non-layered groups, a standard method for determining rock origin on aerial photography. Even though igneous and metamorphic rocks sometimes form layered sequences (and in the Fort Bliss area metamorphic rocks do), by far the largest proportion of layered rocks are sedimentary. Non-layered rocks are necessarily either igneous or metamorphic, and in the Fort Bliss area, they are igneous. Standard criteria, including the irregularity of igneous bodies, their lack of linearity, the presence of pervasive jointing, and curved boundaries, were used to make this determination.

Sedimentary Rocks • Limited field work showed that the predominant rock type was correctly identified in photo analysis for each sedimentary mapping unit. Limestone, the most common rock type in the study area, was easily identified because of its typical appearance on aerial photography in an arid climate, i.e. sharp, narrow ridge crests, high resistance to erosion, angularity, and light photo tone. Criteria that identify limestone formed in an arid environment are lacking, or incorrect, in the published literature, and the criteria used here are generally unpublished. Some of the criteria for limestone formed in temperate or humid regions are applicable to those formed in arid regions, but these are few in number. Primarily unpublished criteria were also used to identify sandstone. No new criteria were recognized to aid differentiation among the sedimentary rocks or to differentiate between sedimentary and other types of rocks.

Unless a rock type formed the major part of a mapping unit, it was not noted on the photography. Such rock types included sandstone, conglomerate, and siltstone interbedded with limestone. These rocks are highly calcareous so they have eroded and weathered in a manner similar to soluble, carbonate rocks. The same pattern elements characteristic of soluble rocks, such as pervasive jointing, angularity of outcrop, and scalloping along baseline contours, are most prominent in the calcareous siltstones, sandstones, and conglomerates in interbedded sequences in the Fort Bliss area. The appearance of these calcareous rocks, at least on the 1:100,000 scale photography, is therefore that of limestone, and as a result, these rocks were not identified in units composed primarily of limestone.

During the field work predictions of rock type were confirmed, and correlations between mapping units determined on the aerial photography were verified, i.e. the rocks designated unit L4 in one location were determined to be the same as those designated unit L4 in another. About 60 percent of the study area has been mapped geologically; hence, additional correlations can be made using these maps.* The correlations for the sedimentary rocks in the study area are shown in table 4.

TABLE 4. Correlations Between Sedimentary Photo Mapping Units and Published Geological Data.

Photo Unit	Published Geological Data
L4	Montoya and El Paso Limestones (Richardson) Montoya and El Paso Limestones with some Hueco and Magdelena Limestones (Dunham) Montoya Dolomite, El Paso Limestone, and Fusselman Dolomite (Harbour, 1972)
L5	Hueco Limestone (Richardson; Schmidt and Craddock) Magdelena Formation and Hueco Limestone (Harbour, 1972)
L6	Hueco Limestone, lower division (King, et al.) Hueco Limestone (Schmidt and Craddock)
L7	Hueco Limestone, middle division (King, et al.) Bliss Sandstone, El Paso and Montoya Formations (Pray, 1961)
L8	NO INFORMATION
L9	Magdelena Group, Yeso Formation, San Andres Formation (Pray, 1961)
L10	NO INFORMATION

*See references for a listing of geological publications on the Fort Bliss area.

A problem appears to exist with units L5, L6, and L7 on the eastern side of the study area within the Hueco Limestone on published maps. The two lower divisions of the Hueco Limestone identified by King, et al. correlate with units L6 and L7 in the southern part of the study area.⁵ No published data exists for the area around Campbell Tank butte where unit L5 is best exposed, so the correlation between unit L5 and the Hueco Limestone cannot be made in this area. The Hueco Limestone mapped by Richardson, Schmidt and Craddock, and Harbour was not subdivided.⁶

The rock type prediction made in photo analysis for unit L9 in the Sacramento Mountains is incorrect. Based on application of standard photo interpretation criteria, unit L9 was identified as sandstone. These criteria include an angular, joint-controlled, coarse-textured dendritic drainage pattern; long, straight stream segments; deep, narrow, steep-walled canyons; broadly rounded ridge crests and spurs; moderate resistance to erosion; and light photo tone. Pray indicates the rocks in this area include interbedded shales, sandstones, and limestones, but that limestone and shale predominate.⁷ Sandstone forms about 14 percent of the rocks included in unit L9, and it appears that the sandstone pattern elements obscured the limestone and shale photo patterns to the point that the sandstone pattern predominated. This suggests that the sandstone is not calcareous. Further work is needed to refine or better define criteria used to identify sandstone in an arid environment in particular, in addition to identifying sedimentary rocks in interbedded sequences.

Also, a major problem exists in correlating the photo mapping units in the Sacramento Mountains with the mapped geological formations. It is obvious from Pray's work that the Sacramento Mountains have been uplifted far more than had been thought from the photo analysis.⁸ Essentially, the Hueco Limestone, the lowest stratigraphic unit in the southern part of the Hueco Mountains, has been uplifted so much that it is in the middle of the stratigraphic sequence in the Sacramento Mountains. The difference in elevation between these two positions is about 270 meters (900 feet).

⁵P. B. King, et al., Hueco Mountains.

⁶G. B. Richardson, Franklin Mountains; Paul Schmidt and Campbell Craddock, Jarilla Mountains; and R. L. Harbour, Northern Franklin Mountains, 1972.

⁷Lloyd C. Pray, Sacramento Escarpment, 1961.

⁸Ibid.

The area mapped as unit L7 in the Sacramento Mountains was mapped as Bliss Sandstone, El Paso Limestone, and Montoya Limestone by Pray.⁹ The formations correspond to units L3 and L4 in the Franklin Mountains. Pray shows the lower portions of unit L9 as part of the Magdelena Group (limestones), which appears elsewhere in this study as part of unit L5. The area designated colluvium on figure 3 (CO) is underlain by Hueco Limestone and the Abo Formation (limestone, shale, and sandstone), and the upper portion of unit L9 is mapped by Pray as Yeso and San Andres Formations (mainly limestones).

Igneous Rocks • Igneous rocks were correctly identified as such in photo analysis. Analysis was made of the photo pattern elements of igneous rocks to derive information on composition (color/tone) and grain size, which are the basis for the classification of igneous rocks. Standard photo interpretation criteria to identify intrusive igneous rocks in an arid environment were successfully applied. These include the absence of linear patterns and regularity, the presence of jointing, and curved boundaries. Most of the criteria used are present in the published literature, including papers by Belcher, et al., Frost, et al., Lueder, and Way and in *Military Geology*.¹⁰ Analysis of hand specimens showed that compositions are slightly more silicic than predicted.

Granitic rocks were all correctly identified as such on the aerial photography using the criteria listed above. In addition, curvilinear sheeting joints and a rounded, lumpy texture were recognized as probably indicative of granitic rocks. Curvilinear sheeting joints, usually subparallel to the land surface, result from the release of pressure as a result of unloading. They are common to granitic rocks and occur in only one other type of rock, gneiss, which is distinguishable from granitic rock because of its lower resistance to erosion in this climate; linearity; generally darker photo tone; and rougher, more uneven, knobby photo texture. Curvilinear sheeting joints can be seen on vertical aerial photography on side slopes.

⁹Lloyd C. Pray, *Sacramento Escarpment*, 1961.

¹⁰D. J. Belcher, et al., *Igneous and Metamorphic Rocks*; Robert E. Frost, et al., *Photo Interpretation of Soils and Rocks*; 1953. Donald R. Lueder, *Aerial Photographic Interpretation*; and Douglas S. Way, *Terrain Analysis*.

Where curvilinear sheeting joints and vertical joints occur together, a texture is produced on granitic rocks that can only be described as rounded and lumpy.* This texture is apparent on aerial photography on outcrops as well as on large bodies of granitic rocks, where it is superposed onto the common domal shape. A rounded, lumpy texture has been observed on granitic rocks on aerial photography ranging in scale from 1:10,000 to 1:120,000. It is also apparent in the field at all scales in semi-arid and arid environments. If the vertical joints are very closely spaced, granitic outcrop will appear blocky on the aerial photography; but when viewed closely in stereo, the blockiness is found to be rounded, rather than angular (see figures 3, 4, 10, 11, 12, and 14). More observations are required to determine whether this texture is characteristic of granitic rocks in all climates.

Previous research by Frost; Frost, et al.; and Leuder, among others, has stated that the identification of the intermediate composition and grain size igneous rocks is very difficult on aerial photography, and this statement is partially confirmed in this study.¹¹ In their classifications of igneous rocks as applied to aerial photography, most authors, including Belcher, et al.; Frost, et al.; *Military Geology*; Avery; von Bandat, and Way discuss only compositional extremes, basalts, granites, and occasionally the fragmental (pyroclastic) rocks.¹² The basis for these classifications is that the rocks with similar grain sizes will appear similar on aerial photography; but other directly observable characteristics, photo tone in particular, readily enable identification of at least three groups of igneous rocks on aerial photography - dark-toned (mafic composition), medium-toned (intermediate composition), and light-toned (silicic composition). If the end members can be identified, the intermediate members, i.e. those left over, should at least be included in a separate group.

Igneous rocks with intermediate compositions were identified as such on the aerial photography, but predictions of grain size, based on analysis of photo texture (the way the rock material looks on the stereo aerial photo) were not always correct. Intermediate composition was correlated to medium photo tone. New criteria to identify the fine-grained, intermediate composition (andesitic) igneous rocks on aerial photography include long, smooth slopes; blocky peaks; vertical jointing; a medium to dark gray photo tone; and a rough, blocky photo texture.

*Other rock types, such as sandstone, conglomerate, and gneiss, also appear rounded, but in these instances, the rounding is due to weathering and not to jointing. Their textures are uneven and knobby, not lumpy.

¹¹Robert E. Frost, *Evaluation of Soils and Permafrost Conditions*, 1950; Robert E. Frost, et al., *Photo Interpretation of Soils and Rocks*, 1953; and Donald R. Lueder, *Aerial Photographic Interpretation*.

¹²D. J. Belcher, et al., *Igneous and Metamorphic Rocks*; Robert E. Frost, *Photo Interpretation of Soils and Rocks*, 1953; *Military Geology*; Eugene T. Avery, *Interpretation of Aerial Photography*; Horst F. von Bandat, *Acrogeology*; and Douglas S. Way, *Terrain Analysis*.

The intermediate composition rocks in the study area include units N2 and N4. No problems were encountered with unit N2, but rock type identification in unit N4 was partially incorrect in the Organ Mountains. Unit N4 was identified in photo analysis as andesitic or dioritic, i.e. intermediate composition and fine to medium grained. Dunham shows that the northeast area of unit N4 is a medium-grained quartz monzonite, and the southwest area is a porphyritic rhyolite, similar in description to unit N2 in the Franklin Mountains.¹³ Compositional and grain-size predictions were basically correct for the southwest part of unit N4 in the Organ Mountains, but were incorrect for the northeast part.

Metamorphic Rocks • The metamorphic rocks in the study area pose a different problem than either the igneous or sedimentary rocks. Their classification and nomenclature are based on their chemistry rather than on a combination of chemical and physical properties; thus, they are very difficult to identify in a hand specimen, much less on 1:100,000 scale aerial photography. In most cases, metamorphic rocks can only be correctly identified under a petrographic microscope. Sedimentary rocks, for example, are classified by grain size; a clastic rock with sand-sized particles is a sandstone, regardless of the composition of the individual grains. The grain size of a metamorphic rock, on the other hand, has nothing to do with its classification, which is dependent on the temperature and pressure regime in which the rock was formed. A low-grade metamorphic rock formed from a sedimentary rock such as shale, for example, would contain quartz, muscovite, chlorite, albite, epidote, and tourmaline. When subjected to more heat and pressure, chlorite and tourmaline disappear because they become unstable and are replaced by biotite, which is stable under the new pressure/temperature conditions. Because of this compositional complexity, metamorphic rocks are usually ignored in discussions of rock type identification criteria on aerial photography, or are treated structurally/texturally, i.e. as gneissic, schistose, or slaty. A systematic approach leading to the identification of metamorphic rocks by composition rather than by texture/structure has not as yet been developed. All metamorphic rocks in the study area, however, were correctly identified as metamorphic in photo analysis. This was done by a process of elimination rather than on the basis of inherent characteristics or photo patterns of the particular rock. The combination of the various characteristics of each of the metamorphic rock units did not correlate with the characteristic patterns of any igneous or sedimentary rock, so units L1, L2, and L3 were assumed to be metamorphic.

¹³Kingsley C. Dunham, Organ Mountains.

Some general characteristics, not specific identification criteria, were used to interpret metamorphic rocks correctly on aerial photography. Two such characteristics are metamorphic grade and occurrence. Metamorphic grade can be determined by evaluating the resistance of a rock to erosion; the higher the grade, the denser and harder the rock and the more resistant it is to erosion. High-grade rocks, those highly resistant to erosion, include quartzite, amphibolite, and granulite. Low-grade rocks, those less resistant to erosion, include some greenschists, phyllite, and hornfels.

The way a metamorphic rock occurs can also provide clues to rock type. Metamorphic rocks occur either locally or in regional terrains, and the types of rocks in each occurrence can differ. Those that occur locally include eclogites, blueschists, and serpentinite, and those that occur in regional terrains include greenschist, amphibolite, and granulite. Some rocks, such as greenschist, marble, and quartzite, can occur in either way. However, if the interpreter can determine the type of occurrence, he can significantly reduce the number of possible rock types with which he has to deal.

Published identification criteria did not serve as an aid in identifying metamorphic rock units in the study area. According to the criteria listed in table 1, L1, L2, and L3 correlate most closely with a schist, which is what they were predicted to be. The correlations are very poor, however, and based purely on published criteria, one would have to consider these rock units sedimentary. The published criteria for marble were useless because they are so few. As a result of photo analysis of unit L1 at Fort Bliss, several criteria were identified that can aid in identifying marble in the future. These are smooth ridge crests and the fine, smooth photo texture. There are no published criteria for quartzite, which comprises units L2 and L3. Re-evaluating the photography after completing the field work, however, has suggested several criteria that can be tested in future work. These criteria include a high degree of resistance to erosion; high relief; moderate jointing; slightly rounded ridge crests; an angular drainage pattern; steep-sided gullies; and a medium-to-coarse, rough and uneven, photo texture.

The metamorphic rocks in the Franklin Mountains are local in occurrence and result from contact metamorphism. This was not recognized, however, until the rocks were field checked, so units L1, L2, and L3 were identified as among those rocks that occur in regional terrains. They were also identified by structure/texture rather than by rock type (composition). Relative metamorphic grade, however, was correctly interpreted on the photography.

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TABLE 5. Correlations Between Metamorphic Photo Mapping Units and Published Geological Data.

Photo Unit	Published Geological Data
L1	Lanoria Quartzite (Richardson) Castner Limestone and Lanoria Quartzite (Harbour, 1960)
L2	Lanoria Quartzite (Richardson; Harbour, 1960)
L3	Bliss Sandstone (Richardson) Bliss Sandstone and El Paso Limestone (Harbour, 1960)

In table 5, the correlations between photo-identified metamorphic rock units and lithologic identifications from the published literature, are shown. As noted above, units L2 and L3 were determined to be quartzite as a result of field work, and the only discrepancy in table 5 concerns unit L1. The rock unit was incorrectly identified on the aerial photography as schist; whereas field work suggested it was marble. However, Harbour's detailed mapping of this part of the Franklin Mountains shows that marble is present only in isolated blocks; the majority of unit L1 is quartzite.¹⁴ The only outcrops in unit L1 visited in the field just happened to be within the areas of marble. The areas Harbour designated as marble (Castner Limestone) were noted as different on the aerial photography, but they were thought to result from a change in erosion pattern on steeper slopes rather than from a change in rock type.

¹⁴R. E. Harbour, Precambrian Rocks, 1960.

CONCLUSIONS

1. In the published literature, claims are made that of the igneous rocks, only granite and basalt can be identified on aerial photography, i.e. that one cannot identify rocks of intermediate composition. The results of this research show that

- (a) Although published criteria for granite were found to be valid, newly developed criteria were verified that are even more useful.
- (b) Intermediate composition rocks can be identified on aerial photography. Descriptions of these rocks are provided and can form the basis for developing identification criteria.
- (c) To date, there is no comprehensive classification scheme for identifying igneous rocks on aerial photography.

In this report, it is suggested that such a classification scheme, based on airphoto patterns, can be developed for the full range of igneous rocks.

2. In this study, it is stated that the existing criteria for metamorphic rocks are too general and that they do not appear to be applicable in arid regions. A basis, depending on type of occurrence and metamorphic grade, was laid for the development of criteria for metamorphic rocks in this environment.

3. These results are applicable to

- (a) Manual techniques of feature extraction for developing digital data bases, such as those required by the Defense Mapping Agency (DLMS, TTADB).
- (b) Terrain analysis.
- (c) The selection of engineering sites, the location of mineral resources, and the location of engineering materials.

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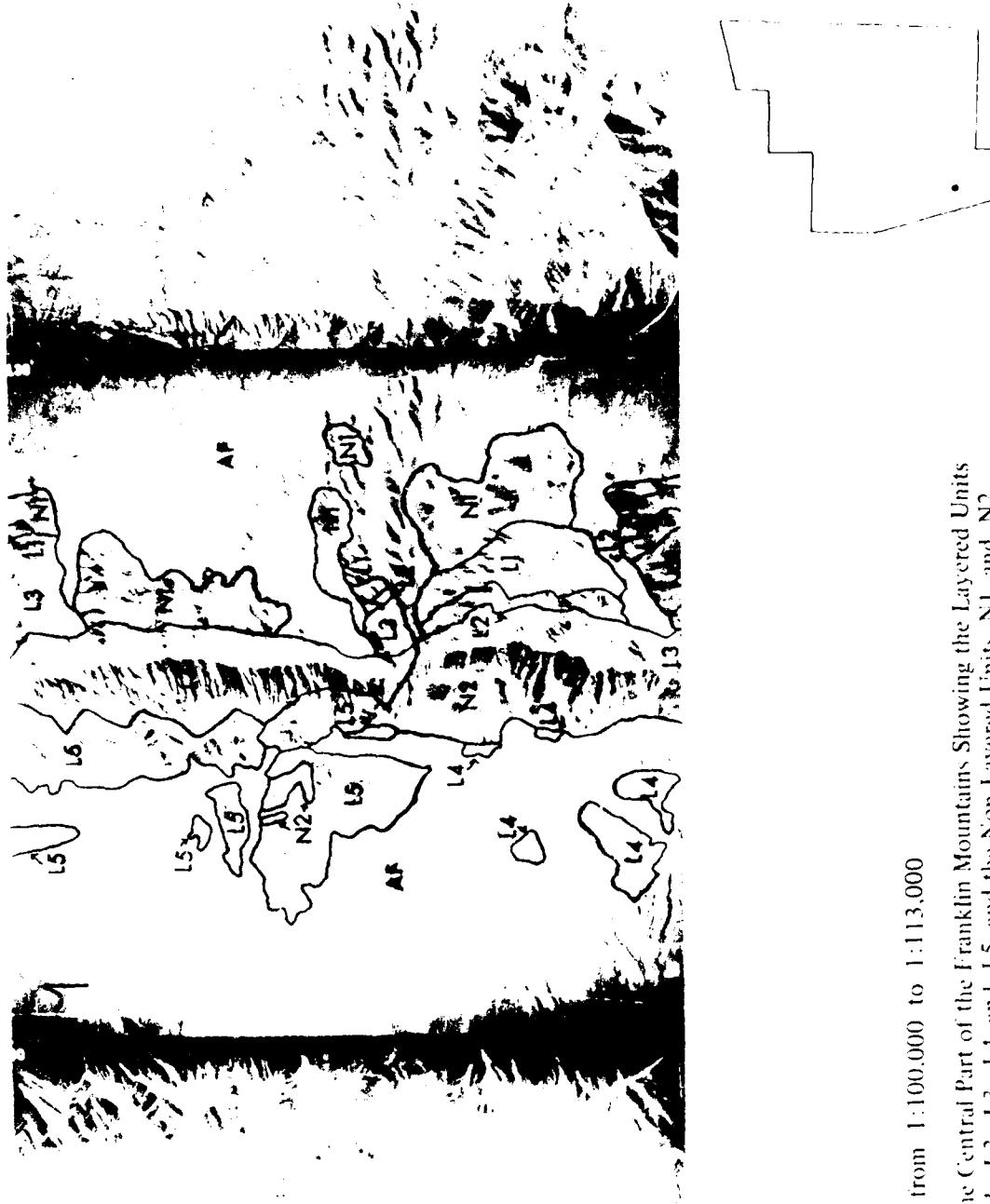
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Scale: Reduced from 1:100,000 to 1:113,000

FIGURE 4. The Central Part of the Franklin Mountains Showing the Layered Units L1, L2, L3, L4 and L5 and the Non-Layered Units N1 and N2.

APPENDIX

PREDICTIONS OF LITHOLOGIC TYPES

Layered Rocks • Unit L1 is located on the east side of the Franklin Mountains along the Transmountain Highway (figures 2, 3, and 4). The photo pattern elements defining unit L1 are shown in table 2. Faint layering suggests that unit L1 is sedimentary rock. The ridge crests are most like limestone ridge crests, but the photo tone is too dark for limestone in this climate (table 1). In addition, differences in hardness, which are characteristic of limestone sequences, are not apparent on the ridge slopes and spurs. Unit L1 has none of the characteristics of layered igneous rock (flow material) either (table 1). The alternative is that unit L1 is a metamorphic rock, probably a low-grade schist or a slate. The layering suggests unit L1 was originally sedimentary.

Field observations show that unit L1 is a marble, rather than a schist. It consists of alternating bands of recrystallized reddish-tan calcite crystals and pinkish- or greenish-gray bands (figure 5). The layers are very thin, ranging from less than 1 millimeter up to 25 millimeters in thickness. The darker layers are probably dolomitic in composition because they effervesce very slowly in dilute hydrochloric acid. Large reddish-brown idocrase porphyroblasts are associated with the dolomitic layers.

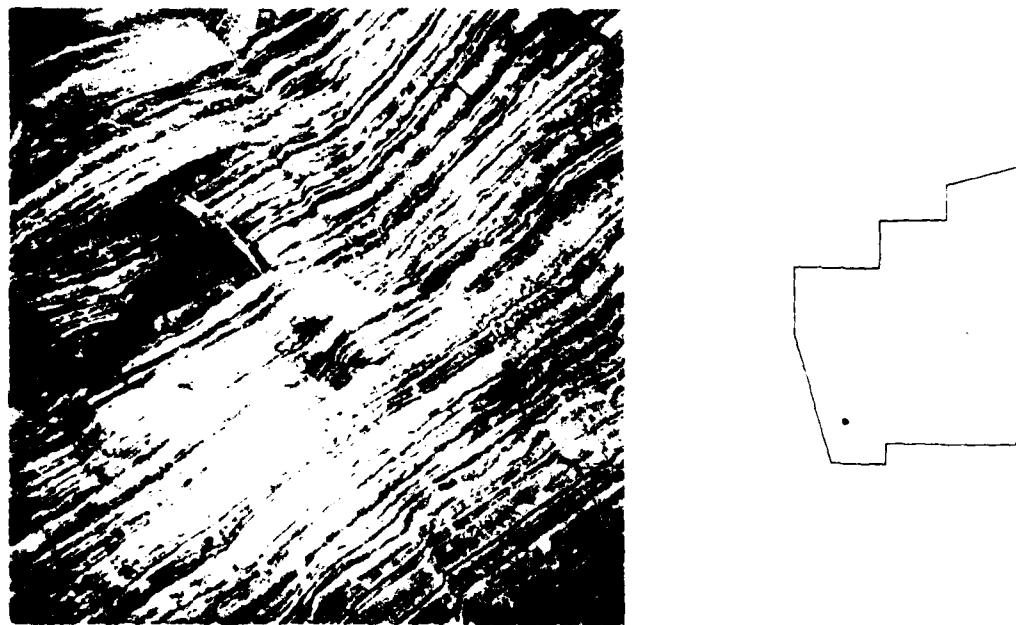


FIGURE 5. Close-up of the Marble Forming Unit L1.

Unit L2 is located in the central part of the Franklin Mountains, stratigraphically above unit L1 (figures 2, 3, and 4). The photo pattern elements of unit L2 are shown in table 2. Sedimentary characteristics, such as layering, are stronger in unit L2 than in unit L1, but if L1 is metamorphic and if the two units are conformable, which they appear to be, then unit L2 is probably metamorphic also. The prominence of layering can be explained by a sedimentary origin. Unit L2 is higher in metamorphic grade than unit L1 because it is more resistant to erosion. Higher grade rocks, such as gneiss, are usually regional in occurrence, not local, and it is highly unlikely that a gneiss would directly overlay a lower grade schist. The light-toned resistant layers may be quartzite, and the less resistant, darker toned layers, similar in appearance to unit L1, are probably low-to-medium grade schist like unit L1.

Unit L2 was field checked just north of the Transmountain Highway (figure 6). It is quartzite, and ranges in color from light to dark gray. The medium-toned, darker gray layer, thought to be schist on the aerial photography, is a darker gray quartzite with occasional black stringers of very fine grained material. The quartzite dips 35°W .



FIGURE 6. Quartzites of Unit L2, Just North of the Transmountain Highway.

Unit L3 occurs in the northern and central Franklin Mountains (figures 2, 3, and 4). In the northern Franklin Mountains, it overlies unit N1 and along the Transmountain Highway, it overlies unit N2. It always immediately underlies unit L4. On the photography, the contacts between units N1 and L3 and between units N2 and L3 appear to be unconformities - they are irregularly curved. In one location, unit L3 overlies unit N2, indicating it is younger than L2. Unit L3, described in table 2, is probably metamorphic like units L1 and L2. The lighter toned layers of unit L3 do not appear to be as resistant as their counterparts in unit L2, so they are probably a competent schist, perhaps a quartz schist, rather than quartzite. The darker toned layers are probably a low-to-medium-grade schist like their counterparts in unit L2.

Field investigations show that unit L3 is a pink or reddish quartzite. The darker toned layers identified as schist on the photos are the darker, reddish quartzite. Unit L3 is much more extensive than determined in photo analysis, extending from the Transmountain Highway area, south to the tip of the Franklin Mountains. Dips at the southern exposures were about 20°W .

Unit L4 is located in the northern and southern Franklin Mountains, on Bishop Cap, and in the southeastern leg of the Organ Mountains (figures 2, 3, and 4). There is no question that it is sedimentary in origin (table 2). Layering is very prominent, and the continuity of the layering is maintained over a large area. The sharp ridge crests, light photo tone, and high resistance to erosion are characteristic of limestone in an arid region (table 1). The less resistant, darker toned layers may also be limestone, because they are not soft enough to be shale and they are not rounded like sandstone.

Field observations show that unit L4 is limestone, as predicted in photo analysis, with some shale partings in the southern exposures (figure 7). Dips at the southern exposures ranged between 33° and 36°W , but along the Transmountain Highway, dips were over 50°W .

Unit L5 occurs as a relatively continuous unit between McGregor Range Camp and Route 506 in the Hueco Mountains and in the northern Franklin Mountains. It forms part of Bishop Cap, and also occurs as inselbergs of varying size surrounding the Jarilla Mountains and in the Hueco Mountains (figures 2, 3, 4, and 8). Unit L5 is the lowest stratigraphic unit on the eastern side of the study area, and the highest unit on the western side. The photo pattern elements of unit L5 are shown in table 2. In addition to the stratigraphic position of unit L5 (above unit L4), layering, linear boundaries that parallel unit L4, and stair-step topography, suggest

it is sedimentary rock (figure 9). Rills on the darker toned layers, indicative of a high clay content, and the smooth, fine, photo texture suggest that they are shale. The light photo tone, angularity, and ridge-capping characteristics of the lighter toned layers suggest they are limestone.

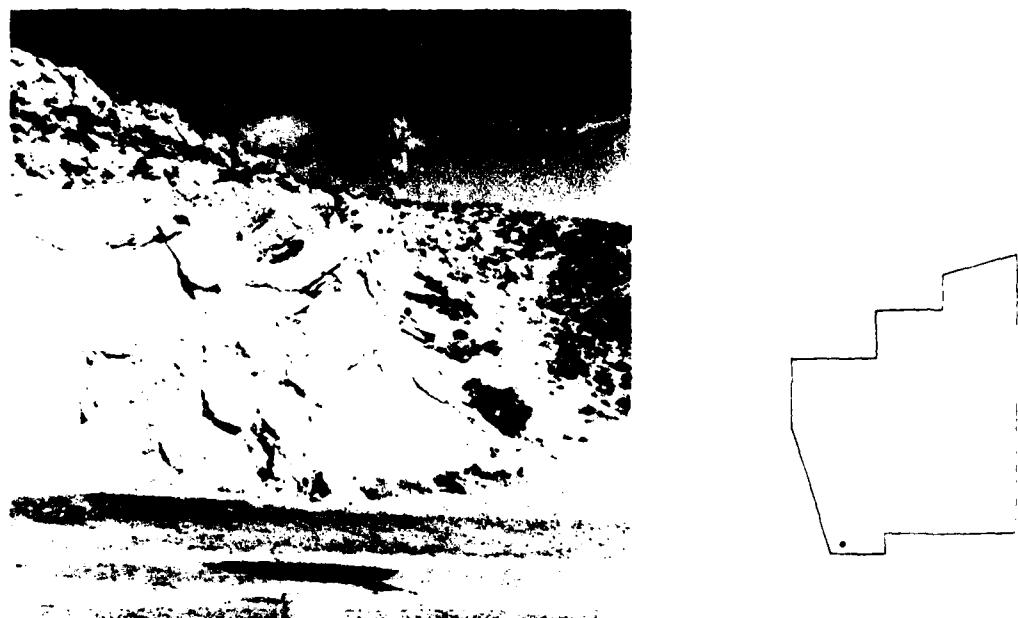


FIGURE 7. Unit L4 at the Southern End of the Franklin Mountains.

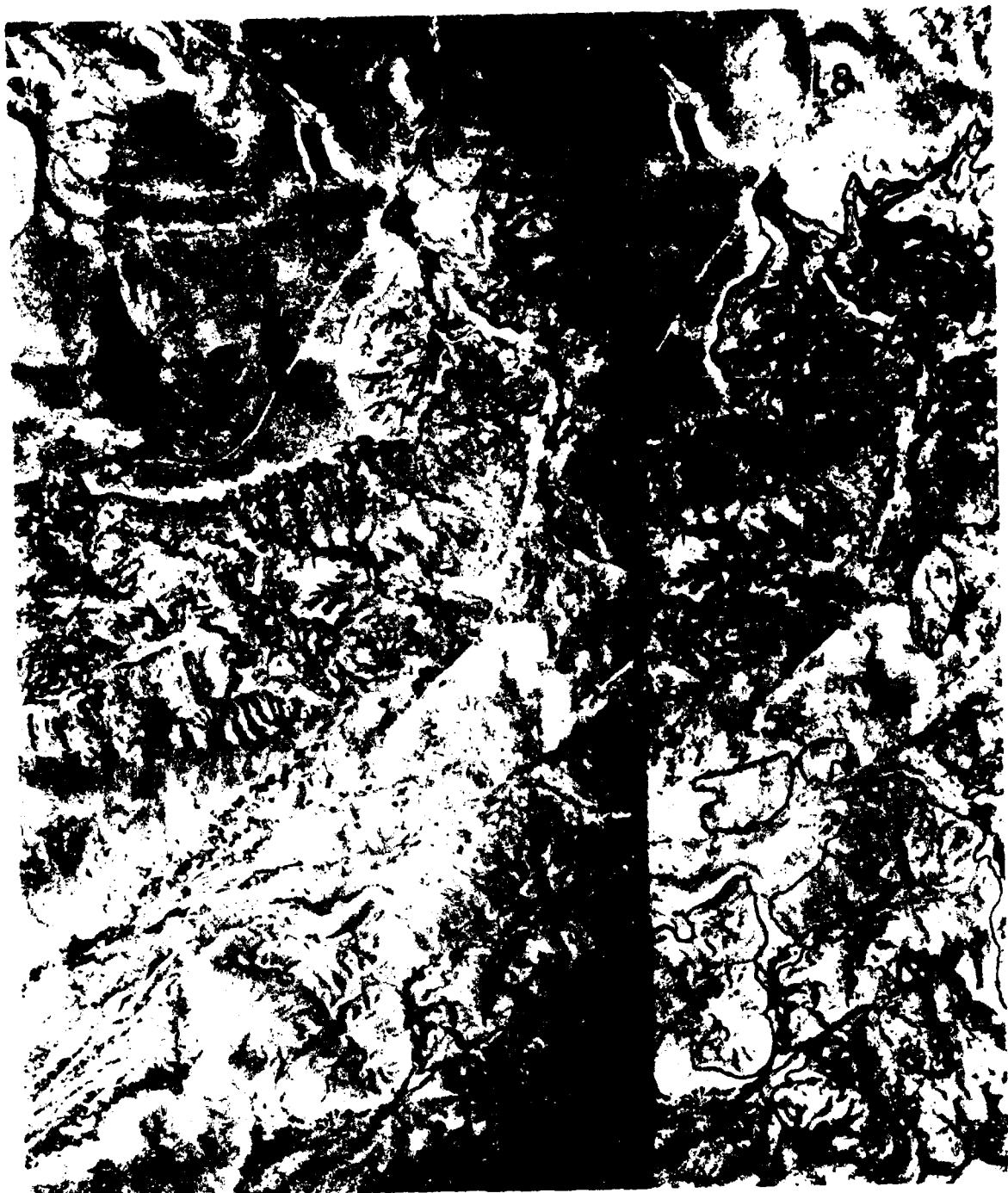
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FIGURE 8. Stair-Step Topography in Unit L5 Near Charley Tank in the Hueco Mountains.

All major exposures of unit L5 on the eastern side of the study area were visited in the field. L5 consists of limestone and shale, as predicted from photo analysis. Dips on the limestone beds range from 5° to 9° E. Limestone outcrops, ranging in color from medium to dark gray, are common, and much of the limestone is fossiliferous. Red and green shale particles were found about 0.3 meter below the soil surface and in small gulleys along the roadsides. A reddish sandstone was found in one location near Campbell Tank. Highly calcareous cream-or buff-colored siltstone and sandy siltstone were commonly found in this sequence in association with the shales. The marked stair-step topography so visible in the aerial photography was surprisingly subtle when viewed on the ground, and the sharply-defined layering on the photography was indistinct when viewed on the ground (figure 9). Shale and siltstone formed the grass-covered stair treads, and limestone formed the shrub-covered risers.

Unit L6 is the largest mapping unit in the study area, forming a continuous exposure from the southern boundary to near Borrego Tank in the Hueco Mountains. It forms a series of inselbergs from Campbell Tank northwest almost to Route 54 and along the fan/mountain boundary north of Borrego Tank (figures 2, 3, and 10). L6 also occurs in the extreme northern and southern parts of the Otero Mesa and in the Jarilla Mountains.



Scale: Reduced from 1:50,000 to 1:59,000

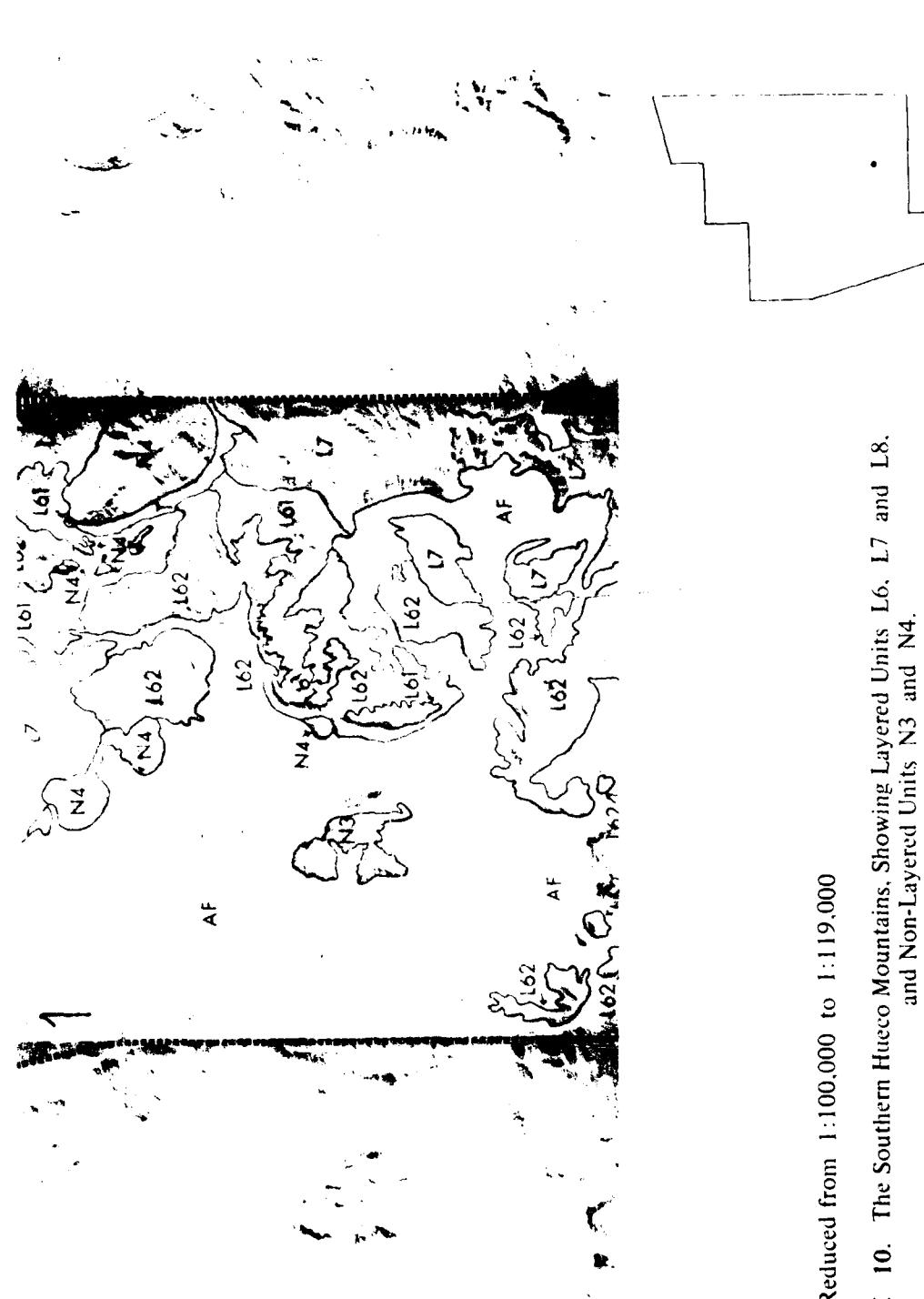
FIGURE 9. Units L5 and L8 Near Campbell Tank.

The stratigraphic relationships, together with the continuity and extent of layering in unit L6 on the aerial photography, indicate that it is a sedimentary rock. Unit L6 consists of two parts as viewed on the 1:50,000 scale photography; the upper part is medium to dark gray in photo tone (L61), and the lower part is marked by a very light toned layer that produces a swirled pattern (L62) and as a result, is more striking (figure 10). None of the more obvious characteristics of either sandstone or shale is present. The prominence of the ridge crests and the high degree of resistance to erosion suggest that both parts of unit L6 are limestone (table 2).

Field observations show that unit L6 not only contains large amounts of limestone, but also numerous sandstone and siltstone beds, along with some shale and conglomerate. The limestone normally ranges from light to very dark gray; cream-colored and fusilinid-rich purple limestones were also encountered. The very light toned layers, so prominent on the aerial photography, are calcareous sandstone (L62, figure 10). The sandstone can be separated from the limestone in the same area on the ground, even though similar in color, because of the rounded appearance of the sandstone beds, which contrasts with the more angular limestone exposures. The swirled pattern of these sandstone beds is the result of erosional processes. Dips on the limestones were 20° E in Pow Wow Canyon, along Highway 180/62, and 6° E near Hackberry Tank.

Unit L7 is located on the lower slopes of the Sacramento Mountains, along the Otero Mesa escarpment in both north and south, in the southern part of the Hueco Mountains as far north as Borrego Tank, and on the southern part of the Otero Mesa (figures 2, 3, and 10). The most continuous exposures of unit L7 are in the Hueco Mountains. The stratigraphic position and continuous layering of unit L7 suggest it is sedimentary in origin. There are no characteristics suggesting that it is composed of either sandstone or shale or that either rock type is present in an interbedded sequence (table 1). Therefore, unit L7 is probably limestone.

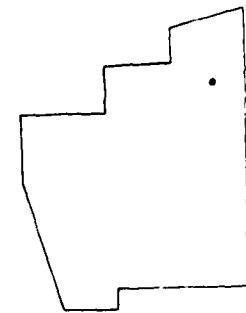
Unit L7 was not visited in the field, but one area designated unit L6 on the photography that was visited in the field is probably part of unit L7. In the upper parts of Hay Meadow Canyon, layering is indistinct with the beds outcropping as flat ledges, which is more characteristic of unit L7 than of unit L6. The hills are rounded, and they are relatively low in height, also more characteristic of unit L7. The limestone bedrock is sparse in comparison to other areas designated unit L6 and visited in the field. Dips in this area range from 2° to 7° E.



Scale: Reduced from 1:100,000 to 1:119,000

FIGURE 10. The Southern Huéco Mountains, Showing Layered Units L6, L7 and L8, and Non-Layered Units N3 and N4.

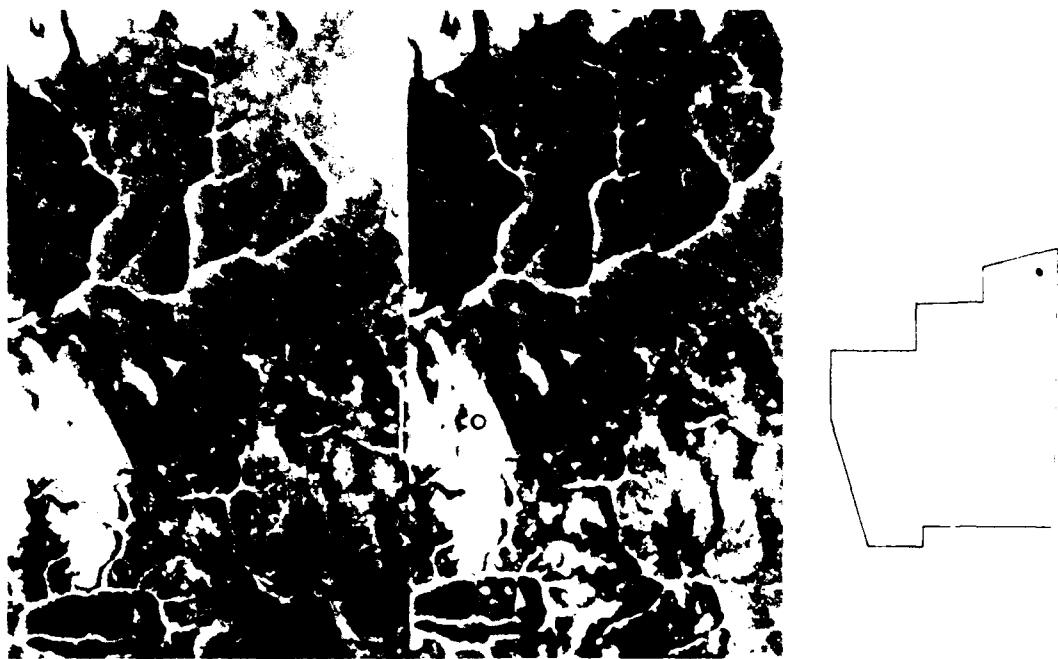
Unit L8 forms the Otero Mesa and the buttes between Ivan Grey and Broyle Tanks below the Otero Mesa escarpment (figures 2, 3, 8, 10, and 11). Table 2 shows the photo pattern elements of unit L8. The stratigraphic position of unit L8 above unit L7 suggests it is also composed of sedimentary rock, as does the presence of layering, although faint or subtle in the photos. Discontinuous drainage, gully cross sections, and sinkholes suggest it is soluble and relatively flat-lying. It is therefore probably limestone. Several areas on the Otero Mesa were visited in the field, as was Campbell Tank butte; the bedrock was medium gray limestone.



Scale: Approximately 1:100,000

FIGURE 11. Units L5, L8, and L10 along the Northern Otero Mesa Escarpment.

Unit L9 occurs only in the Sacramento Mountains (figures 2, 3, and 12). Photo characteristics of unit L9 are shown in table 2. The stratigraphy and layering suggest that unit L9 is sedimentary rock, and there are no indications on the photography that it is either igneous or metamorphic (table 1). The coarse drainage pattern suggests it is formed of permeable materials such as sandstone. The broad, rounded ridges and spurs are typical of sandstone in an arid climate, as is the angular drainage pattern, which suggests joint control. Unit L9 is probably sandstone. L9 was not visited in the field because of difficult access.



Scale: Approximately 1:100,000

FIGURE 12. Unit L9 in the Sacramento Mountains

Unit L10 extends south from Route 506 to just south of Hay Meadow Tank (figures 2, 3, and 11). It forms a narrow, discontinuous band along the base of the Otero Mesa escarpment, except south of Hay Meadow Tank where it forms a bench. In table 2, the photo patterns of unit L10 are shown, although indistinct, indicates L10 is a sedimentary rock. The presence of layering, bounded contours of units L5, L6, and L7, and knobs, and the lack of shale in this unit suggest it is probably sandstone.

Unit L10 clearly underlies units L7 and L8, and probably unit L6. In some places, however, it appears to overlay unit L5, but underlie unit L5. Its anomalous position in these locations is probably the result of faulting.

Unit L10 overlies unit L6. In some places, it appears to overlay unit L5, probably the result of faulting.

Unit L10 was visited in the field at the southern end of its exposure in Martin Canyon. The rock ranges from a friable, bright red to red-orange sandstone to a highly indurated purple-red sandstone. The dip of the darker rock is 28°W and that of the brighter rock is between 8° and 10°E. The dip reversal is probably due to faulting. Unlike other sandstones in the Fort Bliss area, unit L10 is not calcareous. Unit L10 was also found in the Otero Mesa escarpment.

Non-Layered Rocks • Unit N1 forms most of the Jarilla Mountains and is present on the lower slopes in the northern and eastern Organ Mountains and in the eastern Franklin Mountains (figures 2, 3, and 4). The photo pattern elements of unit N1 are shown in table 2. The absence of linear and regular pattern features, the rugged topography, and the curvilinear upper boundaries in the Franklin Mountains suggest unit N1 is igneous rather than metamorphic in origin. The lumpy photo texture suggests unit N1 is coarse grained, and the light photo tone suggests it is silicic in composition. These are characteristics of granitic rock, as are the curvilinear sheeting joints, so unit N1 is most likely granitic in composition.

Unit N1 is the lowest unit wherever it occurs, except in the Jarilla Mountains. In the central part of the Franklin Mountains, it underlies unit L1; but elsewhere in the Franklin Mountains, it underlies unit L3. The curvilinear boundaries between N1 and these layered units are roughly parallel to the boundaries between the layered units. The curved boundaries suggest the contact is an intrusive contact, rather than a fault contact. An intrusion would have contact metamorphosed the rock units above and below it, which would account for the low grade of the metamorphic rock units L1 and L2. The boundaries between N1 and other units elsewhere in the study area are also curved, which suggests N1 is intrusive throughout the study area. Additional evidence of the intrusive nature of unit N1 is present in the Jarilla Mountains; the blocks of sedimentary rock surrounding the mountain range consistently dip away from it, indicating a dome shape. Contact metamorphism probably occurs along all contacts with unit N1.

Unit N1 was field checked along the Transmountain Highway in the Franklin Mountains (figure 13). It is a granitic rock, as predicted, and is probably a true granite — it contains quartz and both feldspars. Fresh rock surfaces are buff or cream-colored. In some places, there is a faint desert varnish. Blocks of unit L1 are present within N1 in this location, indicating N1 was intruded into unit L1. A second, darker colored, coarse-grained rock that contains more plagioclase feldspar is located upslope from the granite. It is probably a quartz diorite or diorite sill.



FIGURE 13. Knob of Unit N1 along the Transmountain Highway in the Franklin Mountains.

Unit N1 was also field checked in the Jarilla Mountains, where it is a medium- to coarse-grained rock, probably a monzonite (figure 14). Quartz is absent, and both plagioclase and potassium feldspars are present, along with hornblende. A large amount of hydrothermal alteration was found in association with ironstones and flow-banded rhyolite along the borders of the intrusion in one location. Some highly altered granitic float was also found in this area.

Unit N2 forms a series of peaks along the crest of the Franklin Mountains, in the central, highest part, overlying unit L2 (figures 2, 3, and 4). It breaks the horizontal continuity of the layering in unit L4, suggesting it is igneous rather than metamorphic in origin. The blocky textured outcrop suggests unit N2 is fine to medium grained. The dark photo tone suggests it is intermediate in composition, so it is probably andesitic (table 2). Unit N2 probably contacts metamorphosed the sedimentary units above and below it, which accounts for the higher metamorphic grade in unit L2, compared to units L1 and L3.



FIGURE 14. Aerial Oblique View of Unit N1 in the Jarilla Mountains.

Unit N2 was field checked in several locations along the Transmountain Highway (figure 15). In hand specimen, the matrix of the rock is fine grained, as predicted, and dark in color, ranging from reddish, purplish, and brown to almost black. Quartz and potassium feldspar phenocrysts indicate the rock is more silicic than predicted in photo analysis, but it appears to be within the intermediate range predicted. The rock is probably a quartz latite or a rhyolite.



FIGURE 15. Stereo Pair of Unit N2 North of the Transmountain Highway.

Unit N3 is a small unit in areal extent, forming Hueco Tanks and the southeast part of the Organ Mountains (figures 2, 3, and 16). Generally light photo tone, curvilinear sheeting joints, and the rounded, lumpy texture of some of the outcrops suggest unit N3 is granitic in composition (table 2). Hueco Tanks was visited in the field, and based on hand specimen analysis, the rock appears to be either a quartz monzonite or a quartz diorite (figure 17). The rock is probably granitic in the Organ Mountains as well. The boundaries of unit N3 in the Organ Mountains are quite straight, suggesting it was uplifted along faults to its present position (figures 3 and 16).

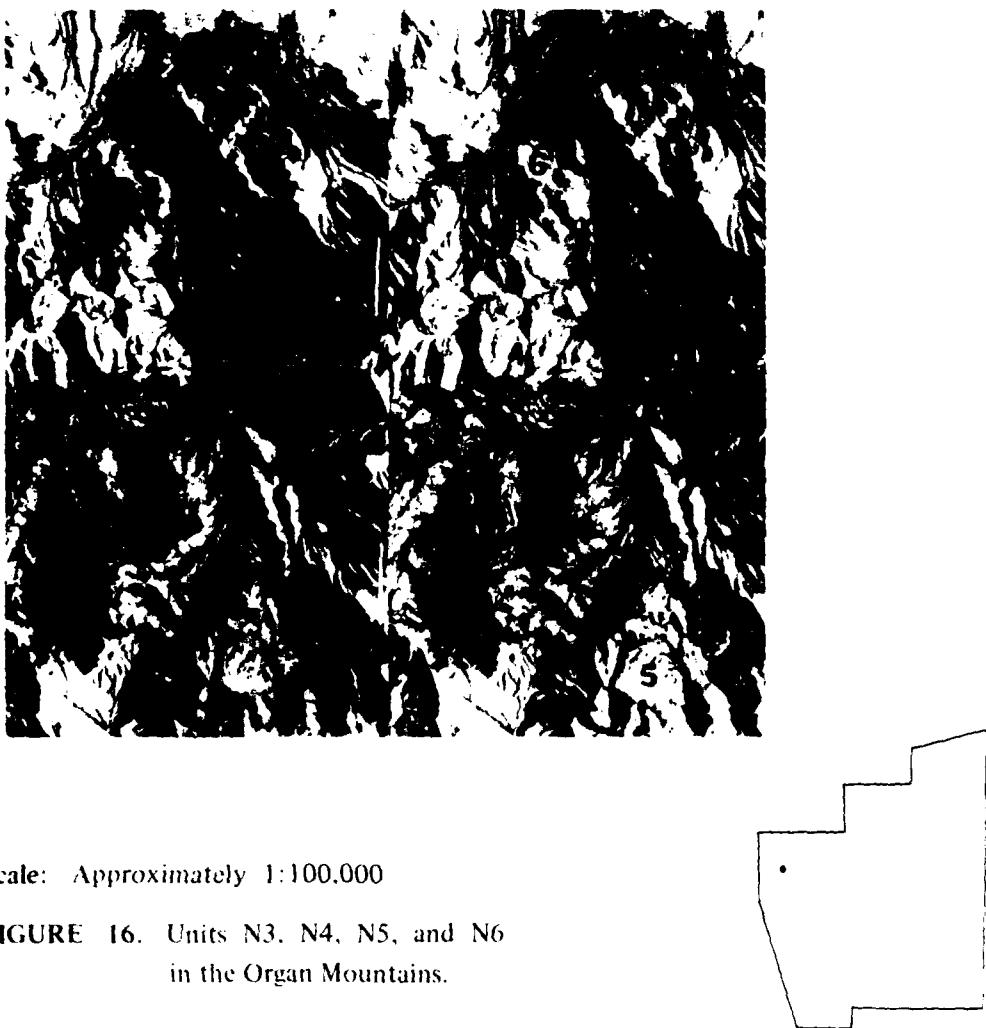




FIGURE 17. Unit N3 at Hueco Tanks.

Unit N4 is the most extensive non-layered rock unit in the study area. It occurs as inselbergs around the Jarilla and Franklin Mountains; as isolated bodies within the sedimentary units in the southern Hueco Mountains (Cerro Alto and Red Hill); and as large areas in the Jarilla Mountains and in the southwestern and northeastern parts of the Organ Mountains (figures 2, 3, and 16). The prevalence of vertical jointing, the medium photo tone, and the rough, blocky photo texture (table 2) suggest that unit N4 is fine-to medium-grained, intermediate composition igneous rock, probably either andesitic or dioritic.

Although Unit N4 was not field checked, samples were collected from Red Hill and Cerro Alto in 1978. The rock is light gray. One sample has a fine-grained matrix with hornblende phenocrysts, along with some quartz, so it is probably a dacite. Others are comparable in composition, but are medium to coarse grained, probably quartz diorites or quartz monzonites. An exposure of unit N4 in the Jarilla Mountains is shown in figure 18.

Unit N5 occurs only in the Organ Mountains (figures 2, 3, and 16). The photo pattern elements of this unit are shown in table 2. The light photo tone indi-

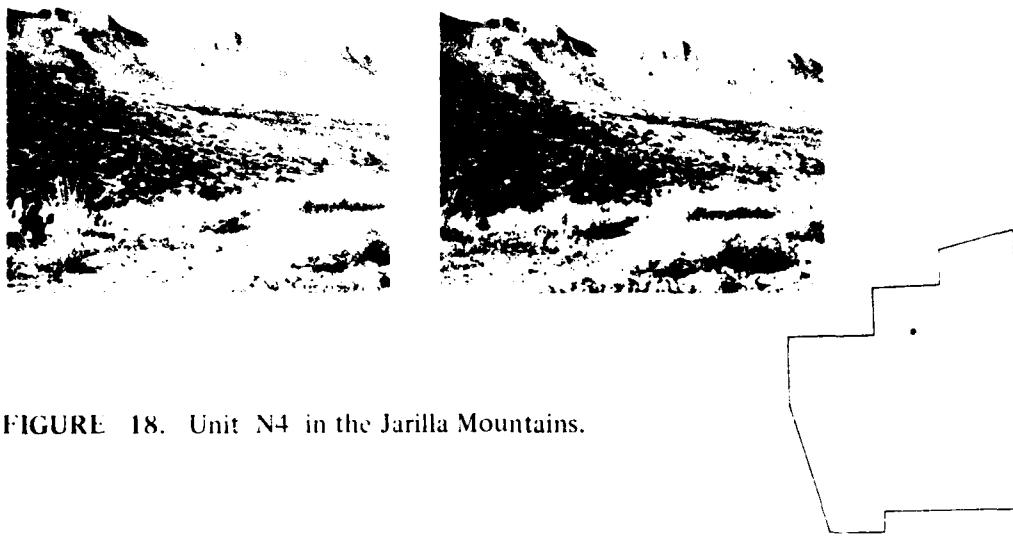


FIGURE 18. Unit N4 in the Jarilla Mountains.

cates it is silicic in composition, and the blocky textured outcrops and fine-textured slopes suggest it is fine to medium grained. Unit N5 is probably a rhyolite or diorite. Unit N5 was not field checked because entry into the Organ Mountains is prohibited.

Unit N6 forms the northern part of the Organ Mountains, the highest elevations in the study area (figures 2, 3, and 16). The photo pattern elements of unit N6 are shown in table 2. The light photo tone, the curvilinear sheeting joints, and the presence of spires suggest it is granitic in composition. Unit N6 was not visited in the field because of restricted entry.